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Landslide investigation using SAR Interferometry on selected regions of Idukki district, Kerala, India

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Landslide, a disturbance in the slope stability causing alteration in the slope profile can be triggered by nature or anthropogenic activities. It is important to monitor the landslide spots so that the devastating effects in resources, human life and economy can be minimized. This paper analyses landslide disasters in Devikulam taluk of Idukki district, Kerala with SAR (Synthetic Aperture Radar) Interferometry technique considering the torrential rainfall of 2018 (June - August) using Sentinel-1 C band (5.36 GHz) SAR data. Fourteen ground truth landslide locations coincided with interferogram observations. On the CartoDEM derived slope, 22 slides were observed to be located in steep slope, 5 slides in moderate slope and Polinjapalam slide was located in rolling terrain. The overall accuracy of the study in preliminary detection of landslides through the interferogram was computed to be 48.72 %. The vertical displacement was quantified in the range -0.755 m to -0.008 m proving the technique is effective.

[Keywords: Disaster, Interferometry, Landslide, Rainfall, SAR, Sentinel-1]

Introduction

Landslides are abrupt hazards involving slope failures, debris flow and rock movement due to soil erosion and cause a significant devastation in resources and human life. So far, the highest economic damage caused by mudslides in the period from 1900 to 2016 was estimated as 989 million U.S. dollars in Peru[1]. Therefore, landslides in tropical countries where heavy monsoon rains are common form a risk to people, buildings, and roads. During rainfall, in a spot prone to landslides, if water continuously drips over the failed surface, the chance of recurrence of landslides is high. Building roads and structures with improper grading of slopes, drainage pattern are the reasons behind human induced landslides. The corridors are highly susceptible to failure when soil mass remain untreated after the construction of road[2].

The Western Ghats, one of the eight “hottest hot spots” of biological diversity[3] in Kerala, India is prone to shallow landslides and consequent debris flows. There exists a strong upward trend in the number of fatal landslides during the south west monsoon season[4]. To understand the landslides, most landslides were visited and the locations were mapped using a handheld GPS which are often inaccessible during heavy rainfall. One of the most difficult tasks in assessment of the landslide prone areas by field investigations particularly after the incidence of the disaster is the inaccessibility and time consumption. The ideal approach would be focusing the landslide prone areas through remote sensing techniques.

Continuous monitoring of landslide hotspots is made possible through remote sensing techniques to prevent future damages and in providing early warning. As a caution, multi spectral data helps in identifying landslides without actually going to the field, only in the absence of cloud cover and are helpful only in hazard zonation and susceptibility mapping. Multitemporal LiDAR (Light Detection and Ranging) Digital Terrain Models allowed the calculation of differential surface, absolute height variations recognizing the main landslide components depletion and accumulation[5]. Hyper spectral data helps in landslide terrain roughness characterization[6]. More advantageous Satellite based active microwave remote sensing technique called SAR (Synthetic Aperture Radar) Interferometry employs microwave (1 m to 1 mm) of the electromagnetic spectrum in which pre-existing ground control is not necessary and it provides a contiguous coverage over a broad area. SAR data are now commonly used for landslide detection and mapping[7]. Satellite radar data, systematically acquired over large areas with short revisiting time, could be used as a tool for mapping unstable areas[8]. Interferometric data pair exploits the phase difference of the waves due to the interaction with the ground surface between two SAR images from slightly different viewing angles to generate digital elevation models which is appropriate even to measure and quantify the fast deformation phenomena, e.g., with displacements ranging from some mm/day to m/day[9].

This study is an attempt to identify the potentiality of Interferometry to provide firsthand information immediately after the disaster in Idukki district of Kerala in India. Landslide locations and details are maintained by Geological Survey of India, the nodal agency to assess landslide hazard in India as an inventory. Debris flow, rock slide and complex slide are the landslide types observed in the database earlier in Devikulam taluk. During the torrential rainfall that started on 8th and 9th June, 2018 nearly 10 Slope failures along fringe slopes of rugged hills bordering the Munnar plateau of Western Ghats, Idukki district have been reported with damaged building, roads, agricultural land from the segment[10]. 'Rock slide' in which soil rocks are transported down the slope, 'Mud flow' involving rapid flow of saturated debris, 'Fall' , a detachment of soil from a steep slope are the kinds of land movements observed in the study area[11] along with which surface vegetal loss is also observed in certain places. Hence, the study area chosen is considered as an ideal terrain for the study of landslides through Interferometry.

The prime objectives of the present study undertaken are as follows: 1. To generate an Interferogram with Sentinel-1 C band Interferometry Wide Swath mode data in VV (Vertical transmit and Vertical receive) polarization for Devikulam taluk; 2. To identify landslide locations preliminarily in Devikulam taluk, Idukki district due to the torrential rainfall of 2018 from Sentinel-1 Interferogram; 3. To validate the landslide locations identified with the ground truth points and investigate the causative factors of the landslide through field study; and 4. To quantify the vertical displacement from the unwrapped interferometric phase information.

Materials and Methods

Study area

About 4.71 % of Kerala is under high landslide hazard category in which 388.32 Km^2 or 8.9 % of land area in Idukki district is prone to high landslide hazard risk. Among the four taluks in Idukki district, Devikulam taluk with a population of 1,77,621 consisting of 12 villages[12] comes under the landslide prone zone area with critical and highly unstable categories based on micro zonation using landslide susceptibility index[13]. Devikulam taluk, one of the 16 threatened ecological locations in the world is stretched between the latitudes of 9°56'56" to 10°21'24" N and longitudes of 77°48'31" to 77°16'14" E covering an aera of 1140.29 Km^2 is shown in Figure 1. The taluk is bounded by Ernakulam district on the West, Theni district on the East, Udumbanchola and Thodupuzha taluks of Idukki district on the South, Thrissur district and Coimbatore district of Tamil Nadu on the North. The river Periyar and Chninnar are the major rivers in the study area.

Methodology

The overall methodology for the study undertaken is depicted in Figure 2 which begin with appropriate study area selection where landslides are reported (Idukki) recently. For successful generation of an interferogram, proper data pair selection with criteria matching baseline estimation, same sub-swath and mode of acquisition etc., are important. In case of small deformation, the spatial and temporal variable state of atmosphere superimposes another signal that infers with the deformation signal which is a main challenge in the preliminary identification of landslides. Then the identified landslides from interferogram were validated with ground truth along with which an investigation is made about the causative factors for the landslide occurrence through interaction with native people. A proper accuracy

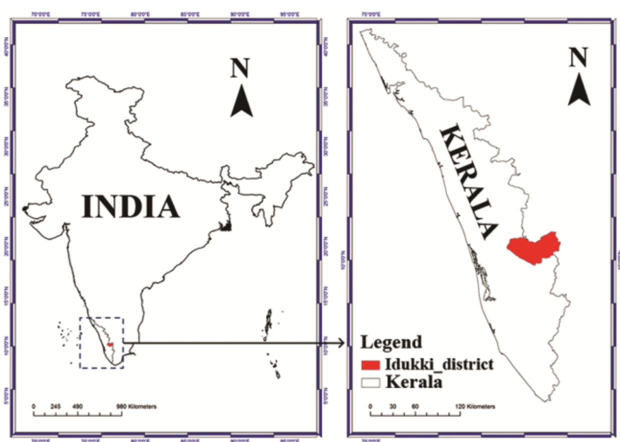

Fig. 1 — Location of the Devikulam taluk in Idukki district, Kerala, India

assessment for the study undertaken was done through confusion matrix or error matrix to establish the reliability of the technique. The vertical displacement was quantified from the phase information obtained from the interferogram after a series of steps like filtering, unwrapping, etc.

Data used

A lot of interferometry satellite missions are available namely ERS-1, 2, UAVSAR, AIRSAR, JERS-1, RADARSAT-1, ALOS PALSAR which is not available for the area under investigation. Unlike optical, Sentinel-1 C Band SAR data of the European Space Agency is not hindered by rainfall and cloud cover. Sentinel-1 operates in the Radar carrier frequency of 5.405 GHz with an incidence angle range of 20° - 46° in dual polarization mode. Sentinel-1 SAR is operated in four nominal acquisition modes namely Standard Stripmap Mode, Interferometric Wide Swath Mode (higher quality of image with ScanSAR form of imaging), Extra Wide Swath Mode (reduced resolution), Wave Mode specifically designed for ocean applications. In Sentinel-1 IW mode, a minimum ground swath width of 250 km is covered with 20 m Azimuth resolution and 5 m Range resolution[14]. The level 1 geo-referenced Slant Range Single Look Complex (SLC) data containing amplitude and phase in real and imaginary parts is resampled to a common pixel spacing grid in range and azimuth and also radiometrically corrected is used in the study[15]. Table 1 depicts the details of Sentinel-1 IW mode images of the study area used in the present study. The temporal revisit time of Sentinel-1 is 12 days in the Vertical transmit and Vertical receive (VV) mode.

Data processing

In the present study, 2-pass methodology depicted in Figure 3 was followed with two SAR scenes and a DEM. The InSAR processing begins with obtaining SAR data (interferometric pair) and generating the interferogram which undergoes processes like filtering and unwrapping finally results in a

Table 1 — Specifications of the Sentinel-1 data used in the present study

Product unique ID	Role of data in pair	Date of acquisition	Criteria of selection
AE69	Master	05/29/2018	Before landslide
9F41	Slave	06/10/2018	After landslides reported

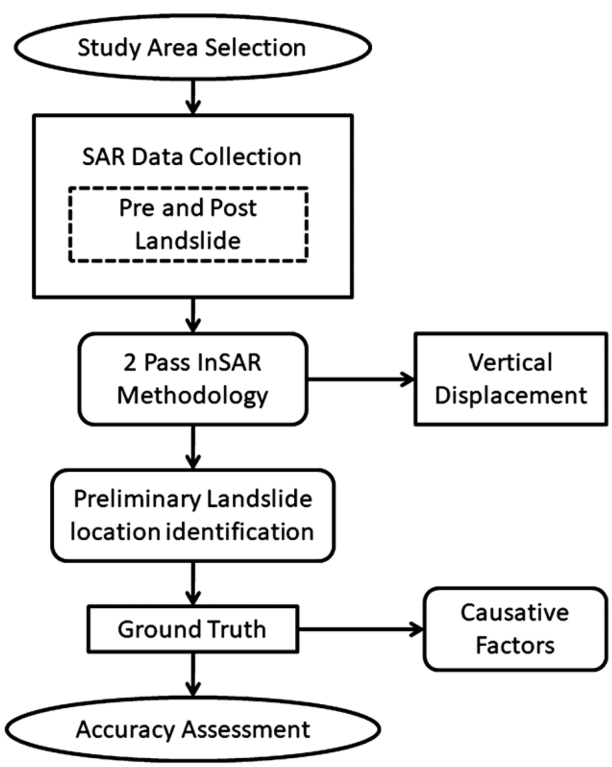

Fig. 2 — Flowchart depicting the methodology followed for the overall study

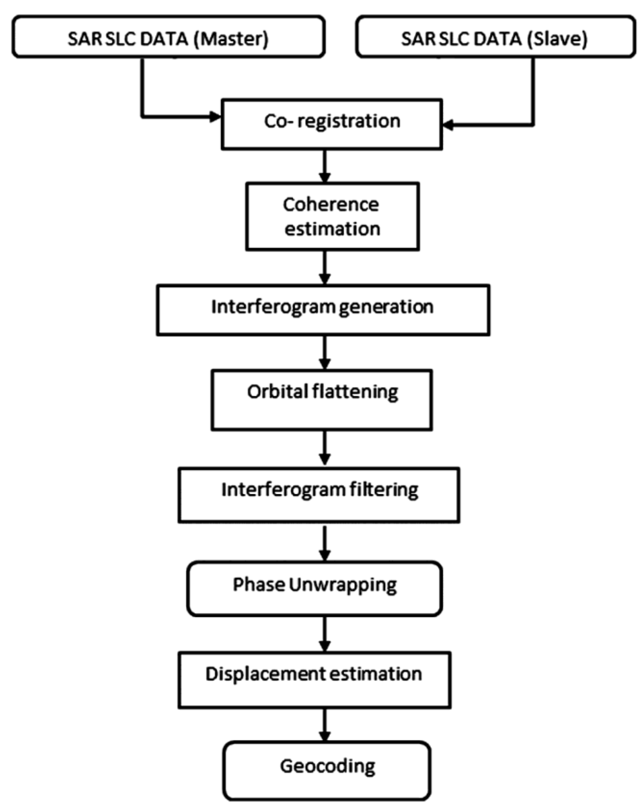

Fig. 3 — Flowchart depicting the 2-pass InSAR technique

displacement map. The height values of the DEM used are converted to synthetic phase values and represented in the geometry corresponding to the real interferogram yielding a resultant interferogram and hence, this method is the fastest. The phase in the resultant interferogram is only dependent on the topography, but the movement influences the phase in the real interferogram. The phase of the resultant and real interferogram when differenced, a differential interferogram with fringes representing only motion is obtained[16].

Interferogram generation

By the process of registration, the SAR images are closely aligned to sub-pixel resolution with native geo-referencing information available in the image to an accuracy of 0.1. The SAR Interferogram is generated by cross-multiplying, pixel by pixel; the first SAR image with the complex conjugate of the matching pixel in the repeat image and the result is a complex image whose phase is the interferogram[17]. The phase of the product image shows the interference effect in the form of fringes and is called interferogram to which the topography is directly related.

Interferogram filtering and flattening

The deburst interferogram formed from full-resolution, contains significant phase noise. The phase noise was reduced with a filter that matches power spectra to the local phase and the fringe visibility was improvised[18]. The phase ramps in the interferogram due to imaging geometry are removed to make unwrapping easy by orbital flattening. The orbital flattened interferogram exhibits the phase variations due to elevation above a reference level.

Phase unwrapping

Unwrapping removes the ambiguities in the interferogram that are some multiples of 2π and reconstructs the phase for the estimation of topography or surface deformation. Using Statistical - cost, Network – flow algorithm for phase unwrapping with Deformation statistical cost mode, the principal phase value which is not proportional to the correct terrain altitude in the interval (-π to +π) the unwrapped phase was extracted.

The Shuttle Radar Topography Mission Digital Elevation Model is converted into SAR geometry and subtracted from the interferogram to isolate the phase component due to displacement from topography. The unwrapped phase is converted to displacement by the relationship in the established Equation (1) shown below

$$d = (\Delta\Phi_{d*}\lambda)/\ 4\pi\ ,$$

Where, $\Delta\Phi_d$ is the change in phase, λ is the wavelength used (here it is 5.6 cm).

Geocoding

All the results are directly geocoded into a map projection by Range doppler terrain correction. The heights in the image coordinate system are terrain corrected to WGS 84 geodetic map reference system by use of Range doppler approach and resampling.

Slope identification

The Digital Elevation Model obtained as geo-referenced CartoSat-1 data with 2.5 m spatial resolution and 250 m location accuracy was used to generate the slope of the study area. The generated slope was then classified using Soil Terrain model[19] to identify the most prone terrain to landslides in the region as shown in Figure 4.

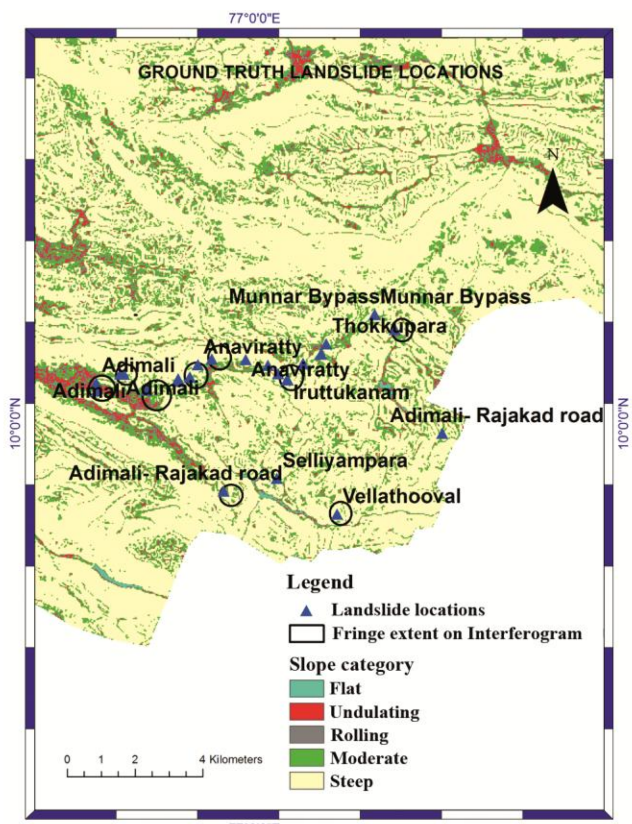

Fig. 4 — Landslide ground truth points on the CartoSAT-1 derived categorized slope map visually checked with the interferogram fringe extent

Field study

Landslide locations were obtained with a mobile GPS on September 17, 2018 around 05:30 p.m. During the field visit, the temperature varied from 23 °C – 30 °C and wind speed ranged from 0.96 m/s to 2.1 m/s. Certain places were under restoration and certain places still contained the debris brought from flood. Few settlements still remained half damaged during the visit. 34 locations were spotted and the rest slides were inaccessible like slides at Adimali, Konnathady and Thokkupara which can be accessed only by trekking. With field visit, it was identified that after the torrential rains, the landslide was not restored but the soil movement significantly stopped.

Accuracy assessment

A visual check is done by simply overlaying the ground truth points over the extent of interferogram fringe generated to see whether the landslide locations fell on the fringes of the interferogram as depicted in Figure 4. A confusion matrix contains information about the actual and predicted or observed classification by a system for which the true values are known. Performance of such a system is evaluated using data in the matrix. For accuracy assessment, the confusion matrix[20] was computed with the four different combination of predicted and actual classes 'Rock slide', 'Mud flow', 'Fall', 'vegetal loss' which were the most dominating types of slides observed in the study area during the field visit. The producer accuracy (precision-out of all the classes, correctly predicted landslides) and user accuracy (recall- out of the positive classes, correctly predicted landslides) were computed for each of the classes which represent landslides that were under undetected category. The confusion matrix is employed to statistically assess the accuracy level of the work carried out.

Results and Discussion

The findings of the study undertaken are as follows: 1. High soil movements in the slope failure area prevent the use of phase data because fringes disappear due to loss in coherence; 2. Few minor slides were unidentified as fringes were not generated in the interferogram due to resolution limitation. With a ground range resolution of 14.65 m X 14.65 m, Sentinel-1 identified major landslides; 3. The displacement was computed from the unwrapped phase and the values ranged from -0.755 m to -0.008 m as shown in Figure 5. The negative sign indicates

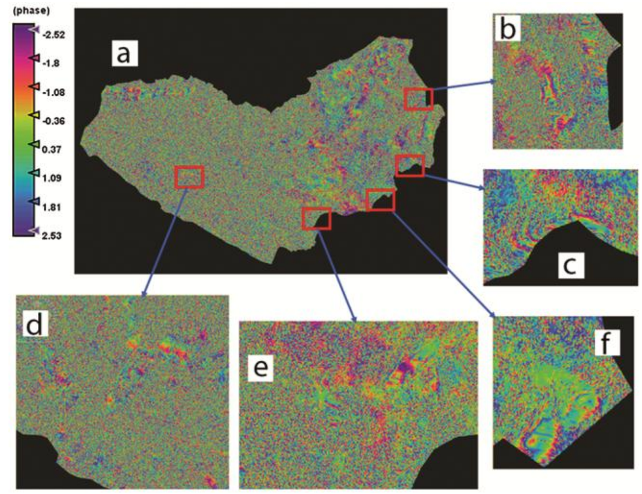

Fig. 5 — Interferogram (a) with disturbed fringes (b - f) observed in various parts of Idukki district

subsidence which is a downward movement of the soil profile in the study region along the Line of Sight of the satellite; 4. Among 28 slides, 22 slides were observed to be located in steep slope, 5 slides in moderate slope and Polinjapalam slide was located in rolling terrain; 5. The slides were triggered when rainwater infiltrated and accumulated along the loose debris due to improper drainage system, overburden loading and loosening for adverse cultivation pattern, unplanned cutting of the roadway; 6. The overall accuracy of the study in just detecting the landslides was computed to be 48.72 % with a precision of 80 % was observed for the vegetal loss category.

The coherence, a spatial indicator of the quality of interferogram between the master and slave data ranged from 0.018 to 0.987. Higher coherence values are observed from features like settlement and rocky escarpments with consistent scattering. The interferometric phase image represents a map of the relative terrain elevation with respect to the slant range direction. The fringes similar to contour lines represent 2π ambiguity and the phase difference due to displacement. Out of 29 ground truth locations of landslides obtained from field visit, 14 landslides were observed on the fringe extent obtained from interferogram. The deformation of the surface is identified through the occurrence of fringes as shown in Figure 6. One fringe corresponds to half a cycle of wavelength of the signal used to acquire the data[21]. The phase of the interferogram was observed in a range of -3.137 to 3.14. This phase of topography-flattened coherence images was used to map small movements in a slope-failure area[22]. The ground truth

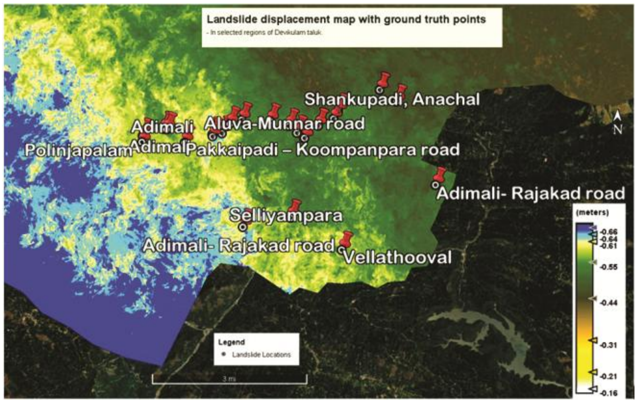

Fig. 6 — Landslide displacement map obtained through Interferometry along with ground truth points majorly scattered along the Southern regions of the district

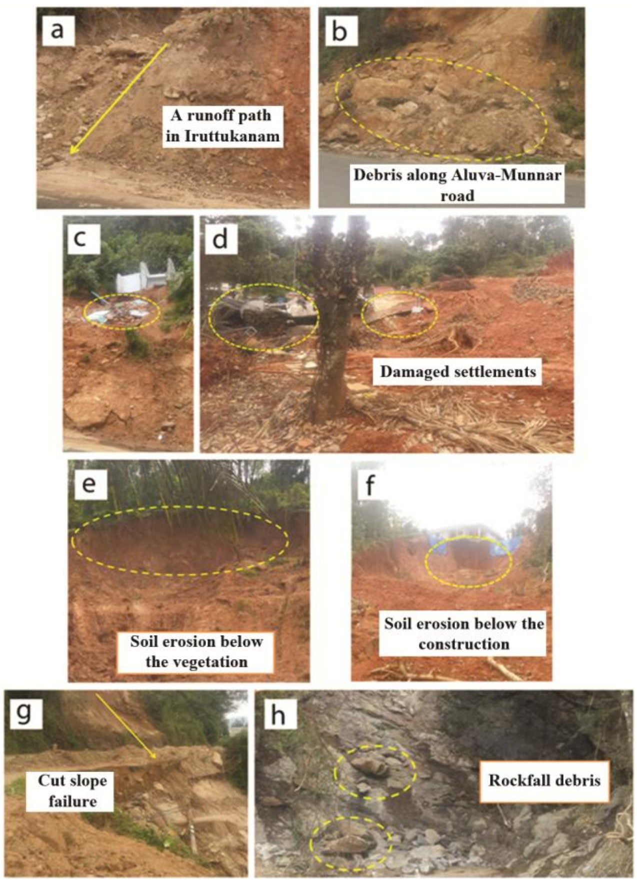

Fig. 7 — a) Field photograph showing run off path, b) Debris, c and d) Damaged settlement, e)Vegetal loss and Soil erosion, f) Soil erosion below the construction, g) Cut slope failure, and h) Rock fall debris

locations where landslides were spotted were overlaid on the Cartosat-1[23] derived slope map which was evaluated to 5 classes such as flat, undulating, moderate, rolling, and steep according to SOTER system of classification[19] which revealed that moderately dissected slope and lowly dissected slope is the major form of the landscape features encountered in the taluk. Many landslides were located in the Adimali region of Devikulam taluk due to adequate road construction leading to unplanned cutting and heavy rainfall. In the accuracy assessment, both the rock slides observed in the field visit were detected in the interferogram because the rocky escarpments show consistent scattering unlike places with vegetation. Field visit at certain locations of Devikulam taluk helped us to understand the terrain, causes and after effects of landslide occurrence in the study area as shown in Figure 7.

Causative factors

During the field visit, many observations were made visually and with the help of questionnaire survey from native people. Improper drainage system, overburden loading and loosening for adverse cultivation pattern were identified to be the geo-scientific cause for landslides due to shower. The slides were triggered when rainwater infiltrated and accumulated along the loose debris. During the field visit to a rockfall caused by weathering and erosion at Koompanpara, Aluva- Munnar road, it was found that daily variation of temperature and excess water flow due to rainfall lead to exfoliation. Adding to the process, vegetation growth forced the unstable rock to fall. Construction of building in Ambazhachal without proper strengthening of foundation resulted in load at the head of the slope. Unplanned cutting of the roadway along with incessant rainfall triggered slope failure.

Conclusions

The assessment of landslides with SAR Interferometry, an advanced technology provides measurements at finer resolution. The SAR interferometry technique is effective in preliminarily identification and displacement quantification of landslides helpful in the synoptic investigation of landslides remotely without the limitation of time and climate. The 2-pass method is the most direct way to generate a differential interferogram. The results are effective with appropriate interpretation from ground truth and the performance is measured using the confusion matrix. The method employed in the study gives satisfactory results even in the regional scale.

The accuracy of the displacement obtained depends on the resolution of the data used and resolution of the DEM used to isolate the topographic phase component and can be validated if continuous monitoring is done by establishing ground control points. Sentinel-1 C Band has substantial penetration on vegetation and the temporal revisit time of Sentinel-1 being 12 days, if the disaster happens in between, the technique can effectively help in identifying movements in inaccessible areas like forests later for damage assessment.

Scope for future work

The satellite parameters will remain the same and only in the processing end improvisation can be done. If a high resolution DEM component can be obtained by flying UAV over the study region, it can be used to remove the topographic phase component resulting in more precise displacement estimation. When bands with higher penetration like L-band are used, the same technique can provide more accurate results.

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Conflict of Interest

The authors declare no competing or conflict of interests.

Author Contributions

The first author VSK carried out the software processing, field based survey and drafted the manuscript. The second author SSR guided and helped in drafting the manuscript.

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